

Reconstructing the Chelyabinsk event: pre-impact orbital evolution

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ABSTRACT

The Chelyabinsk superbolide was the largest known natural object to enter the Earth’s atmosphere since the Tunguska event in 1908 and it has become a template to understand, manage and mitigate future impacts. Although the event has been documented in great detail, the actual pre-impact orbit of the parent body is still controversial. Here, we revisit this topic using an improved Monte Carlo approach that includes the coordinates of the impact point to compute the most probable solution for the pre-impact orbit ($a = 1.62$ au, $e = 0.53$, $i = 3^\circ 97'$, $\Omega = 326^\circ 45'$ and $\omega = 109^\circ 71'$). We also check all the published solutions using a simple yet robust statistical test to show that many of them have problems to cause an impact at the right time. We use the improved orbit and N -body simulations to revisit the dynamical status of a putative Chelyabinsk asteroid family and confirm that it could be linked to resonant asteroids 2007 BD₇ and 2011 EO₄₀. In addition, and as the classification of Chelyabinsk meteorites is well established, a search for meteorite falls of the same chondrite group and petrologic type gives some evidence for the existence of an associated LL5 chondrite cluster.

Key words: celestial mechanics – meteorites, meteors, meteoroids – minor planets, asteroids: general – minor planets, asteroids: individual: 2007 BD₇ – minor planets, asteroids: individual: 2011 EO₄₀ – planets and satellites: individual: Earth.

1 INTRODUCTION

An asteroidal impact of the magnitude of the Chelyabinsk event has never before been documented in so much detail. Yet it happened during daytime and that makes the analysis of the available observational material much harder. There is full consensus among the scientific community on the dynamical class of the impactor, it was an Apollo asteroid. Also widely accepted is that it was a piece of a larger object and that additional fragments may be following similar orbits (Borovička et al. 2013; de la Fuente Marcos & de la Fuente Marcos 2013, hereafter Paper I; Popova et al. 2013). However, the actual values of its orbital parameters are still a matter of debate and different authors have published solutions for which the overall dispersions in range are relatively large (see Table 1): 31 per cent in semimajor axis, 27 per cent in eccentricity, 49 per cent in inclination, 0.09 per cent in longitude of the node and 24 per cent in argument of perihelion. This translates into multiple theories on possible links between the parent body and certain near-Earth asteroids (NEAs) or groups of them: 86039 (1999 NC₄₃) (Borovička et al. 2013), the Flora family (Itokawa, Popova et al. 2013) or 2011 EO₄₀ and related objects in Paper I.

Here, we revisit the topic of the pre-impact orbit of the Chelyabinsk superbolide using an improved Monte Carlo methodology that includes the coordinates of the impact point. This Letter is organized as follows. The current status of the subject of the calculation of the pre-impact orbit is summarized in Section 2; a

statistically robust impact test aimed at validating candidate orbits is outlined and applied to the published solutions, results are discussed. An improved, most probable pre-impact orbit is found in Section 3. Using the improved orbit and N -body simulations we study the dynamical status of a putative Chelyabinsk asteroid family in Section 4. In Section 5 we introduce some additional supporting evidence in the form of a meteorite cluster analysis. Results are briefly discussed and conclusions summarized in Section 6.

2 THE PRE-IMPACT ORBIT SO FAR

The dynamical class of the Chelyabinsk impactor has been well established since the beginning, calculations by Adamo (2013), Borovička et al. (2013), Borovička et al. (Green 2013), Chodas & Chesley,¹ Emel’yanenco et al.,² Lyytinen,³ Lyytinen, Matson & Gray⁴, Nakano,⁵ Popova et al. (2013), Proud (2013), Zuluaga & Ferrin⁶, Zuluaga, Ferrin & Geens (2013),⁷ and Paper I showed that the parent body was an Apollo asteroid. In contrast, and despite the

¹ http://neo.jpl.nasa.gov/news/fireball_130301.html

² http://www.inasan.ru/eng/asteroid_hazard/chelyabinsk_bolid_new.html

³ <http://www.amsmeteors.org/2013/02/large-daytime-fireball-hits-russia/>

⁴ <http://www.projectpluto.com/temp/chelyab.htm>

⁵ <http://www.icq.eaps.harvard.edu/CHELYABINSK.HTML>

⁶ <http://arxiv.org/abs/1302.5377>

⁷ <http://astronomia.udea.edu.co/chelyabinsk-meteoroid/>

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Table 1. Published solutions for the pre-impact orbit of the Chelyabinsk superbolide tested here. The errors from Popova et al. (2013) are from their Table S5B. Paper I is de la Fuente Marcos & de la Fuente Marcos (2013). The values of the probabilities discussed in the text are also given.

Authors	a (au)	e	i (°)	Ω (°)	ω (°)	$P_{0.050\text{au}}$	P_{r_H}	P_{10R_E}	n_c
Borovička et al.	1.55 ± 0.07	0.50 ± 0.02	3.6 ± 0.7	326.410 ± 0.005	109.7 ± 1.8	0.889	0.231	0.009	440
Borovička et al. (2013)	1.72 ± 0.02	0.571 ± 0.006	4.98 ± 0.12	326.459 ± 0.001	107.67 ± 0.17	1	0.716	0.032	0
Paper I	1.62375 ± 0.00014	0.53279 ± 0.00011	3.817 ± 0.005	326.4090 ± 0.0007	109.44 ± 0.03	1	1	0.897	99499
Nakano ⁵	1.6223665 ± 0.0000001	0.5311191 ± 0.0000001	3.87128 ± 0.00001	326.42524 ± 0.00001	109.70844 ± 0.00001	1	1	0.920	546405
Popova et al. (2013)	1.76 ± 0.04	0.581 ± 0.009	4.93 ± 0.24	326.4422 ± 0.0014	108.3 ± 1.9	1	0.412	0.015	35
Proud (2013)	$1.47^{+0.03}_{-0.13}$	$0.52^{+0.01}_{-0.05}$	$4.61^{+2.58}_{-2.09}$	$326.53^{+0.01}_{-0.0}$	$96.58^{+2.94}_{-1.72}$	0.768	0.183	0.006	0
Zuluaga & Ferrin ⁶	1.73 ± 0.23	0.51 ± 0.08	3.45 ± 0.2	326.70 ± 0.79	120.62 ± 2.77	0.341	0.071	0.001	15
Zuluaga et al. (2013)	1.27 ± 0.05	0.44 ± 0.02	3.0 ± 0.2	326.54 ± 0.08	95.1 ± 0.8	0.245	0.068	0.002	0
Zuluaga et al. ⁷	1.368 ± 0.006	0.470 ± 0.010	4.0 ± 0.3	326.479 ± 0.003	99.6 ± 1.3	0.250	0.173	0.007	0
average $\pm \sigma$	1.6 ± 0.2	0.52 ± 0.04	4.0 ± 0.7	326.49 ± 0.09	106 ± 8				
This work	1.624765 ± 0.000005	0.53184 ± 0.00001	3.97421 ± 0.00005	326.44535 ± 0.00001	109.71442 ± 0.00004	1	1	0.919	148765

multiplicity of published orbital solutions, the actual pre-impact orbit of the parent body of the Chelyabinsk superbolide (see Table 1, the rest can be found in Paper I) is still controversial. The overall ranges for the orbital elements are in some cases too large for comfort (see above). Any computed orbit must be consistent with an obvious fact, on 2013 February 15, 03:20:33 GMT a superbolide was observed in the skies near Chelyabinsk, Russia.

The orbital elements and therefore the position of our planet at the time of the impact are well known (see Table A1 and Appendix A). Any acceptable orbital determination must put the parent body in the immediate neighbourhood of the Earth on that day and time. The orbital parameters of any given solution are characterized by errors and any analysis of the validity of a given orbit must be discussed in statistical terms. If, for a certain solution, the probability of being close to the Earth at the impact time is below a reasonable threshold, the orbit must be rejected. Under the two-body approximation, the equations of the orbit of an object around the Sun in space are given by the expressions (e.g. Murray & Dermott 1999):

$$\begin{aligned}
X &= r (\cos \Omega \cos(\omega + f) - \sin \Omega \sin(\omega + f) \cos i) \\
Y &= r (\sin \Omega \cos(\omega + f) + \cos \Omega \sin(\omega + f) \cos i) \\
Z &= r \sin(\omega + f) \sin i
\end{aligned} \quad (1)$$

where $r = a(1 - e^2)/(1 + e \cos f)$, a is the semimajor axis, e is the eccentricity, i is the inclination, Ω is the longitude of the ascending node, ω is the argument of perihelion and f is the true anomaly. Using the above equations and the data in Table A1, the position of the Earth is uniquely determined. For a given orbit with known ranges for the orbital parameters (given by the standard deviations or errors) the impact risk assessment can be performed by means of a Monte Carlo simulation (Metropolis & Ulam 1949).

Let us consider a set of orbital elements (a , e , i , Ω and ω) for the incoming body. These elements are randomly sampled within fixed (assumed) ranges following a uniform distribution. For each set, we randomly sample the above equations in true anomaly for both the object and the Earth, computing the usual Euclidean distance between both points so the minimal distance is eventually found. This value coincides with the minimum orbit intersection distance (MOID) used in Solar system studies. The assumed range for the true anomaly of the Earth is small, equivalent to a time interval of about 6 min, approximately centred at the impact time. In comparison, the time taken by our planet to travel a distance equal to its own average diameter (12 742 km, $R_E = 6371$ km) is

nearly 7.1 minutes. For an object following an impact trajectory, the largest orbital changes take place when it is within 10 Earth radii (R_E) from the Earth's centre (see e.g. Jenniskens et al. 2009; Oszkiewicz et al. 2012). If the predicted perigee (MOID) of an object is mostly (in probabilistic terms) outside $10 R_E$, the actual probability of impact is negligible. Any candidate solution predicting a perigee for the parent body beyond 0.000425 au ($10 R_E$) should be rejected. Our 7-dimensional Monte Carlo sampling provides a robust statistical impact validation for any input orbit. If we apply the algorithm described above to the solutions in Table 1 we obtain Fig. 1. There, we show the distribution in time and geocentric distance for the MOIDs associated with the various solutions. A total of 2×10^7 test orbits have been computed for each solution. The probabilities of having a MOID under 0.05 au ($P_{0.050\text{au}}$) and 0.0004263 au ($10 R_E$, P_{10R_E}) at the time of impact are given in Table 1. Only two orbits have a probability higher than 50 per cent of placing the impactor within $10 R_E$ of our planet at impact time. For objects following the other orbits, the chances of being near the Earth at impact time are smaller, in some cases significantly. Our simple, yet robust statistical test makes just one single and very reasonable assumption: that the data in Table A1 are correct. It may be argued that our impact test is based on the two-body approximation but the impactor penetrates well inside a region where that approximation is no longer valid because the gravitational field of the Earth, not the Sun, is dominant. However, if we focus on a sphere centred on the Earth and of radius equal to the Hill radius of our planet ($r_H = 0.0098$ au) which is the conventional limit for its sphere of influence, we still find problems with most solutions. Any serious candidate impact solution must have a probability (P_{r_H}) close to 1 for the MOIDs to be under one Hill radius around impact time. Only two solutions in Table 1 fulfil that condition. Besides, focusing on the number of orbits reaching a distance to the surface of the Earth < 100 km (the characteristic thickness of the Earth's atmosphere) within 20 seconds of JDCT 2456338.6391296, n_c , the results are also consistent (see Table 1). However, no data on the impact point were used to compute the solution in Paper I.

3 IMPROVED MONTE CARLO ANALYSIS

In Paper I we made a simplifying assumption by considering a point-like Earth, neglecting the geographical coordinates of the impact point (60.32° E, 54.96° N), a hole on the frozen surface of

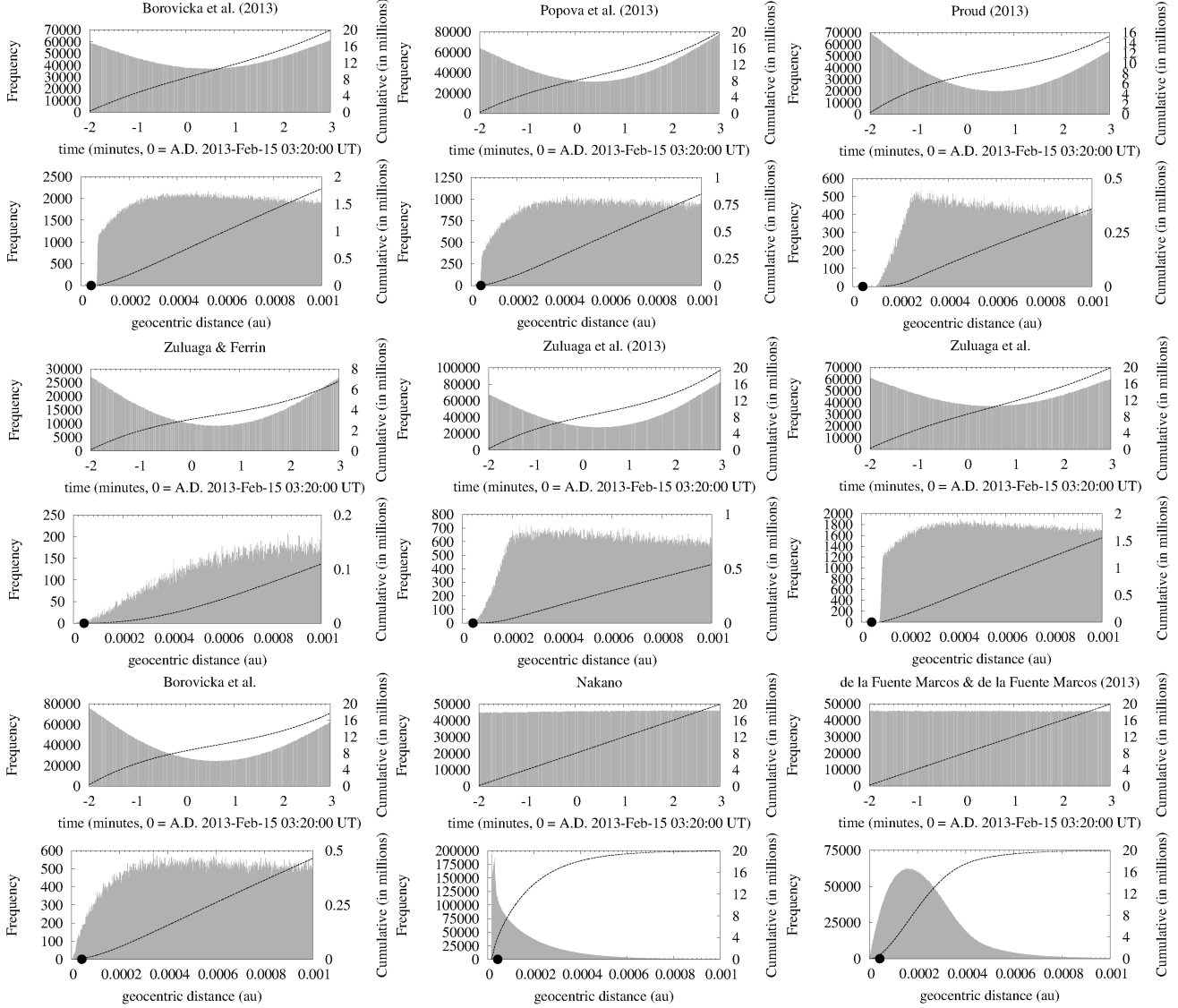


Figure 1. Distribution in time and geocentric distance of the MOIDs associated with the solutions in Table 1. The time is referred to JDCT 2456338.6389 = A.D. 2013-Feb-15 03:20:00. The black dot represents the radius of the Earth. Here and in Fig. 3 the bin size in time is 0.001 min and 0.000001 au in distance.

Chebarkul Lake (Popova et al. 2013). As a result, all the impact points associated with that solution are near the Earth’s equator (green points in Fig. 2), not close to the city of Chelyabinsk. To further improve our previous orbit we computed the coordinates of the impact point for our test orbits as described in e.g. Montenbruck & Pfleger (2000). In computing the longitude of impact, we assume that the MOID happens when the object is directly overhead (is crossing the local meridian). Under that approximation, the local sidereal time corresponds to the right ascension of the object and its declination is the latitude of impact. Instead of using as impact point the hole in Chebarkul Lake, we use the location of the actual atmospheric entry. The superbolide was first detected on 2013-Feb-15 03:20:20.8 \pm 0.1 s UT at longitude 64 $^{\circ}$ 56.5 \pm 0 $^{\circ}$ 03.0, latitude +54 $^{\circ}$ 44.5 \pm 0 $^{\circ}$ 01.8 and altitude 97.1 \pm 0.7 km (see Table S1, Popova et al. 2013, also Miller et al. 2013). The new most probable orbit is not too different from the one in Paper I and, again, matches well the one originally computed by S. Nakano (see Table 1). It was found after about 10^{10} trials. The distribution in time and geocentric distance of the MOIDs associated with our preferred solution

(see Fig. 3) as well as the various probabilities in Table 1 show that this orbit is statistically more robust than any of the published solutions (except Nakano’s). Figure 2 displays its associated path of risk. The particular orbit depicted there (see Table B1) had an altitude of over 97 km at coordinates (63 $^{\circ}$ 9 E, 54 $^{\circ}$ 5 N) and reached perihelion early on 2012 December 31. Geometrically, it is the most probable orbit. Using the coordinates of the hole in Chebarkul Lake gives similar orbital solutions but we believe that our choice is technically more correct.

4 RELATED OBJECTS AND DYNAMICAL EVOLUTION

Assuming that the object responsible for the Chelyabinsk event was a fragment of a larger body (or that other objects move in similar orbits), we use the D-criteria of Southworth & Hawkins (1963), D_{SH} , Lindblad & Southworth (1971), D_{LS} , Drummond (1981), D_D , and the D_R from Valsecchi, Jopek & Froeschlé (1999) to investigate possible dynamical connections between this object and known mi-

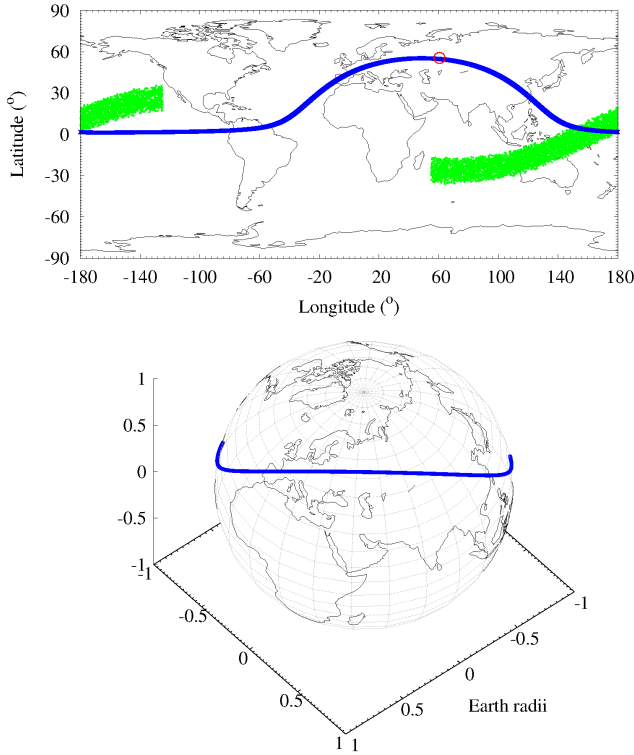


Figure 2. Path of risk for one representative orbit obtained with our improved Monte Carlo analysis; it reached an altitude over the surface of the Earth of 97.26 km at coordinates (63° 90 E, 54° 48 N). The blue curve outlines the flight path (E to W) of the object assuming that it did not hit the ground. The green stripe represents the impact risk associated with the solution in Paper I. The location of the city of Chelyabinsk is also plotted.

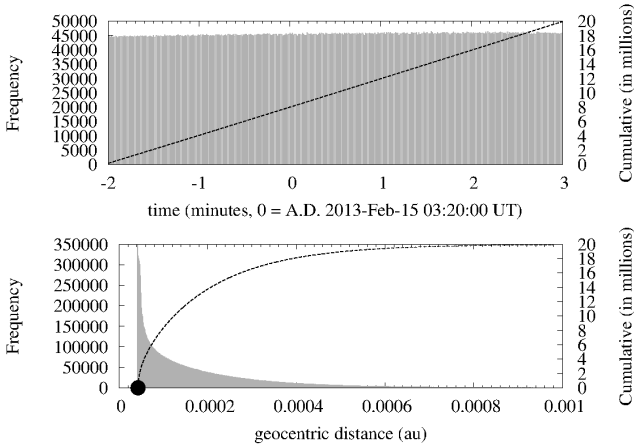


Figure 3. As Fig. 1 but for our preferred solution (see Table 1).

nor bodies. A search among all the objects currently catalogued (as of 2014 April 7) by the Jet Propulsion Laboratory (JPL) Small-Body Database⁸ using these criteria gives the list of candidates in Table B2. With one exception, their orbits are poorly known as they are based on short arcs. All of them are classified as Apollos, NEAs and, a few, as potentially hazardous asteroids (PHAs); their aphe-
lia are in or near the 3:1 orbital resonance with Jupiter (at 2.5 au).

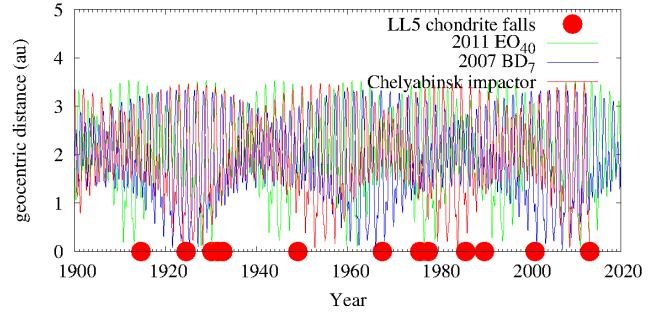


Figure 4. Distance from the Earth to the Chelyabinsk impactor, 2007 BD₇ and 2011 EO₄₀ since 1900. Observed LL5 chondrite falls are also indicated (see Table B3). Note the periodic flybys (see the text for details).

These objects are strongly perturbed as they experience periodic close encounters not only with the Earth–Moon system but also with Mars, Ceres and, in some cases, Venus. They are also submitted to multiple secular resonances (see below). We have studied the short-term past and future orbital evolution of several of these objects using the Hermite integration scheme described by Makino (1991) and implemented by Aarseth (2003). Our physical model includes the perturbations by the eight major planets, the Moon, the barycentre of the Pluto–Charon system and the five largest asteroids. For accurate initial positions and velocities, we used the elements provided by the JPL online Solar system data service⁹ (Giorgini et al. 1996) and based on the DE405 planetary orbital ephemerides (Standish 1998) referred to the barycentre of the Solar system. For more details see de la Fuente Marcos & de la Fuente Marcos (2012) and Paper I.

Figure 4 shows that the pre-impact orbit of the Chelyabinsk superbolide was also affected by multiple secular resonances. The object was experiencing one or more close encounters with the Earth–Moon system at nearly 27 yr intervals. Asteroid 2007 BD₇ follows a similarly recurrent encounter sequence but this time with a period close to 44 yr. Asteroid 2011 EO₄₀ (and 1996 AW₁) also undergoes close approaches to the Earth–Moon system following a rather regular pattern, every 17 yr approximately.

5 AN LL5 CHONDRITE CLUSTER?

It has been suggested that the time of fall of meteorites reflects the orbital distribution of their parent bodies. If the parent bodies of certain meteorites are organized in orbital groups, fragments may collide with the Earth in different years but their calendar dates should exhibit some linear correlation. Studying the existence of meteorites of the same chondrite group and petrologic type that fell within some calendar days of each other in different years may uncover the existence of an orbital group or meteoroid stream. Figures 4 and 5 appear to suggest such a trend (see also Table B3). Encounters at the descending node happen in January/February and encounters at the ascending node occur in June to August. A Plavchan periodogram (Plavchan et al. 2008) gives a most significant period for the LL5 chondrite falls of 17.37 yr with a probability that the detected value is due to chance of 0.0013. The second most significant period is 28.32 yr with a p -value of 0.0083. This is close to the proposed flyby pattern period of the Chelyabinsk superbolide parent body with our planet. Although the evidence is certainly

⁸ <http://ssd.jpl.nasa.gov/sbdb.cgi>

⁹ http://ssd.jpl.nasa.gov/?planet_pos

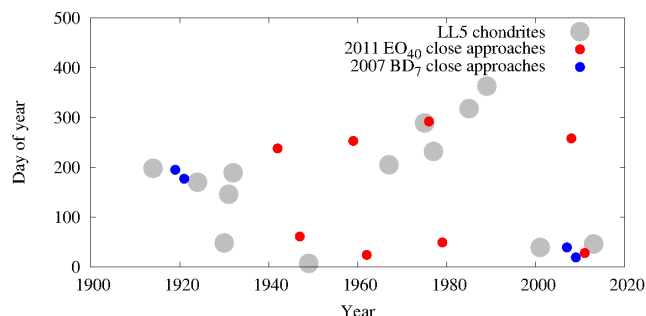


Figure 5. Year-day distribution of LL5 chondrite falls and flybys with asteroids 2007 BD₇ and 2011 EO₄₀ since 1900. Day one = January 1. Sources: see Table B3, JPL Small-Body Database and NEODYs system.

encouraging, we must take these results with caution because the number of observed falls is small.

6 DISCUSSION AND CONCLUSIONS

In this Letter, we have obtained a statistically sound, most probable solution for the pre-impact orbit of the Chelyabinsk superbolide and implemented a simple yet robust Monte Carlo-based probability test to validate candidate solutions. The past dynamical evolution of this most probable orbit is almost a textbook example of how meteorites are delivered to the Earth from the 3:1 orbital resonance with Jupiter (at 2.5 au) as described by e.g. Gladman et al. (1997), see panel C in their Fig. 3. Therefore, the ultimate origin of the Chelyabinsk superbolide can be tracked backwards to the main asteroid belt. The orbit of the parent body of the Paragould meteorite (another LL5 chondrite) has also been traced back to the 3:1 resonance (Nelson & Thomsen 1947). This resonance often pushes minor bodies into the Sun or out of the resonance, towards the inner Solar system, creating transient near-Earth objects. For objects following this evolutionary path and delivered to the region close to the semimajor axis range 1.5–1.6 au, the ν_3 , ν_4 and $2g = g_5 + g_6$ secular resonances are dominant (Gladman et al. 1996; Michel & Froeschlé 1997). This translates into horizontal oscillations in the (e, a) plane (see Fig. B1) as the secular resonances modify e at constant a . The impactor appears to be a dynamical relative of equally resonant asteroids 2007 BD₇ and 2011 EO₄₀. The dynamical relationship is certainly encouraging but the current orbits of these asteroids are not reliable enough to claim a conclusive connection; a genetic link in the form of a mutually consistent chondritic constitution (for the Chelyabinsk meteorites) and the asteroids' surface composition remains to be tested. In the absence of a genetic link, this group of asteroids is still a family but a resonant one. Their current orbital evolution results in a series of periodic close encounters with the Earth-Moon system (at 17 yr intervals for 2011 EO₄₀-like orbits, 27 yr for the Chelyabinsk impactor, or 44 yr for 2007 BD₇-like orbits), due to the combined action of multiple secular resonances. One effect of this peculiar dynamical behaviour is that if one of these objects happens to be in an adverse position for observing from the Earth at the time of its close approach, then the object will remain unobserved for decades. Reaching perigee at small solar elongations makes these objects inherently difficult to discover and track from the ground. This is exactly what happened with the Chelyabinsk impactor. Space-based observations are the only proper way to study this population. However, during their flybys, they are good targets for study by Earth-based radar. If there are

additional objects moving in similar orbits, they may have struck the Earth in the past. Records of meteorite falls of the same chondrite group and petrologic type (LL5) provide some marginal yet consistent evidence in favour of this scenario. A reasonably compatible match between the compositions and physical properties of the Chelyabinsk meteoritic samples and those of any of the other meteorites in Table B3 (see e.g. Olivenza versus Chelyabinsk) will provide definitive support for the analysis completed here.

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Zuluaga J. I., Ferrin I., Geens S., 2013, E&PSL, preprint (arXiv:1303.1796)

APPENDIX A: ORBITAL ELEMENTS OF THE EARTH AROUND THE TIME OF IMPACT

The superbolide was first detected on 2013-Feb-15 03:20:20.8 \pm 0.1 s UT at longitude 64 $^{\circ}$.565 \pm 0 $^{\circ}$.030, latitude 54 $^{\circ}$.445 \pm 0 $^{\circ}$.018 and altitude 97.1 \pm 0.7 km (see Table S1, Popova et al. 2013). Therefore, the actual impact with the atmosphere took place at epoch 2456338.6391296 Julian Date, Coordinate Time. The geometric osculating orbital elements of the Earth within approximately ± 150 s of the first detection are given in Table A1. These values have been computed by the Solar System Dynamics Group, Horizons On-Line Ephemeris System. The time resolution provided by this ephemeris system is one minute and we decided to use JDCT 2456338.6389 = A.D. 2013-Feb-15 03:20:00 as reference; this instant is considered as our $t = 0$ across this work unless explicitly stated. Therefore, we assume that the entry of the superbolide started approximately 20.8 s after $t = 0$. The orbital elements at that time (record in bold in Table A1) have been obtained by interpolation using the data in Table A1.

APPENDIX B: SUPPLEMENTARY MATERIALS

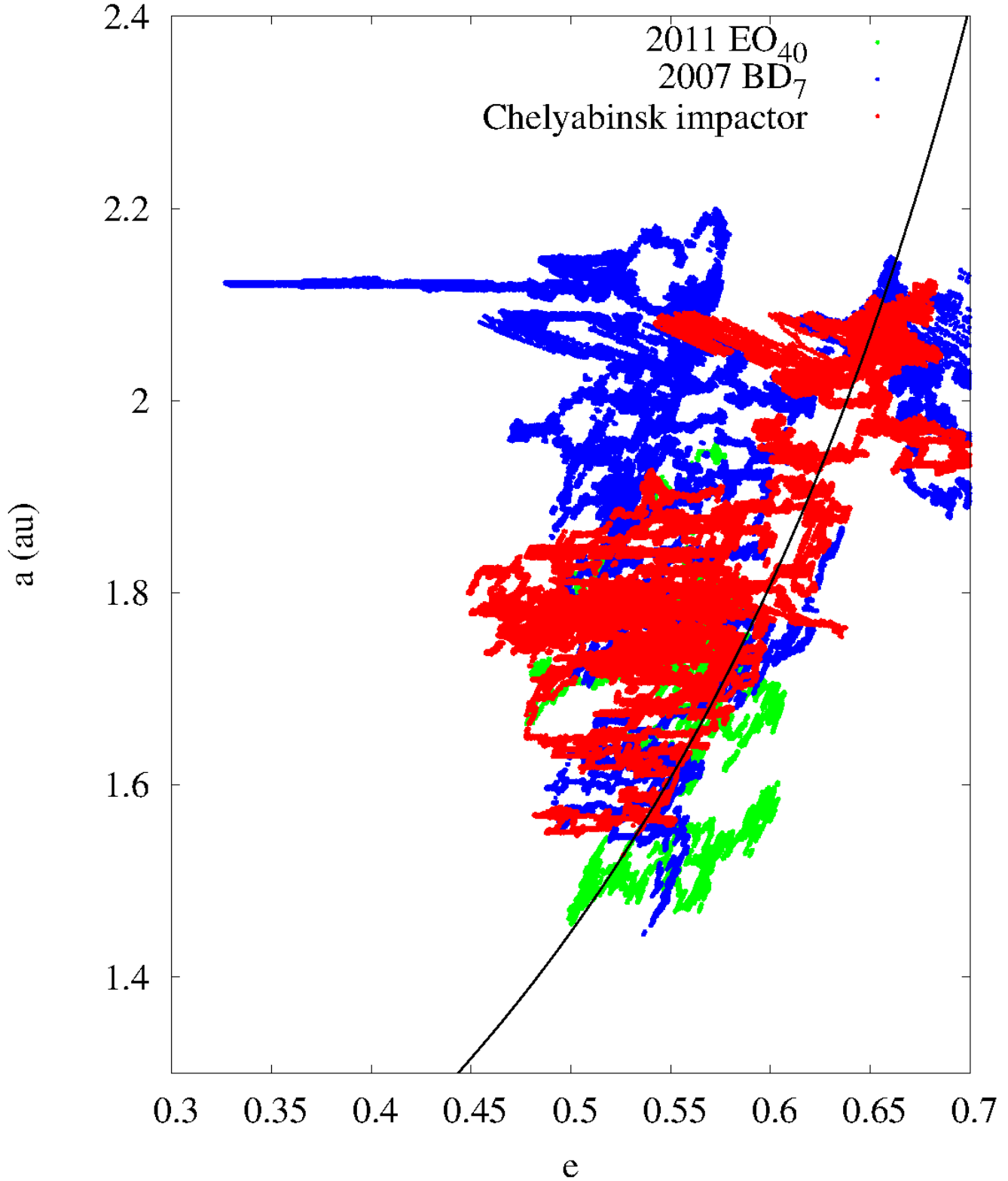


Figure B1. Backwards orbital evolution of the Chelyabinsk impactor, and asteroids 2007 BD₇ and 2011 EO₄₀. The continuous line represents the (e, a) combination with perihelion at the semimajor axis of Venus (0.7233 au). The objects experience multiple episodes of horizontal (resonant) oscillations as in Fig. 3, panel C of Gladman et al. (1996). Our calculations did not include the Yarkovsky effect which may have a non-negligible role on the medium, long-term evolution of objects as small as the ones studied here. Proper modeling of the Yarkovsky force requires knowledge on the physical properties of the objects involved (for example, rotation rate, albedo, bulk density, surface conductivity, emissivity) which is not the case for the objects discussed here. Detailed observations during future encounters with the Earth should be able to provide that information. On the short term, the Yarkovsky force mainly affects a and e . Its effects are negligible if the objects are tumbling or in chaotic rotation. The non-inclusion of this effect has no major impact on the assessment completed. The time is referred to JDCT 2456200.5 = A.D. 2012-Sep-30 00:00:00 and we integrated the orbits for 0.7 Myr.

Table A1. Orbital elements of the Earth around JDCT 2456338.6389 = A.D. 2013-Feb-15 03:20:00 (Source: JPL HORIZONS system). Data as of 2014 April 7.

Epoch JD CT	CT	a (au)	e	i (°)	Ω (°)	ω (°)	f (°)
2456338.637500000	03:18:00.0	1.000460470380130	0.01681075152088699	0.003426162422992692	163.1611470947406	301.5002044683560	41.76083874450404
2456338.638194445	03:19:00.0	1.000460358050270	0.01681064764891284	0.003426287278598604	163.1605191659505	301.5006652233060	41.76170745517870
2456338.638888889	03:20:00.0	1.000460245713456	0.01681054377780261	0.003426412091192330	163.1598915292676	301.5011256430874	41.76257620868673
2456338.6391296	03:20:20.8	1.0004602068	0.0168105078	0.0034264553	163.1596744389	301.5012846926	41.7628774485
2456338.639583333	03:21:00.0	1.000460133369692	0.01681043990755927	0.003426536860777701	163.1592641843954	301.5015857279981	41.76344500502645
2456338.640277778	03:22:00.0	1.000460021018978	0.01681033603818453	0.003426661587351488	163.1586371314587	301.5020454779188	41.76431384419267
2456338.640972222	03:23:00.0	1.000459908661319	0.01681023216968093	0.003426786270908627	163.1580103702289	301.5025048930830	41.76518272618031

Table B1. Representative orbital elements of the parent body of the Chelyabinsk superbolide around the time of impact.

Epoch JD CT	CT	a (au)	e	i (°)	Ω (°)	ω (°)	M (°)
2456338.6391296	03:20:20.8	1.62476552	0.53184298	3.9742124	326.445352	109.714428	21.9204136

Table B2. Orbital elements, orbital periods (P_{orb}), perihelia ($q = a(1 - e)$), aphelia ($Q = a(1 + e)$), number of observations (n), data-arc, and absolute magnitudes (H) of the candidates to be the parent body of the meteoroid that caused the Chelyabinsk superbolide. The various D -criteria (D_{SH} , D_{LS} , D_{D} and D_{R}) are also shown. The objects are sorted by ascending D_{R} . Only objects with $D_{\text{R}} < 0.05$ are shown. Data as of 2014 April 7.

Asteroid	a (au)	e	i (°)	Ω (°)	ω (°)	P_{orb} (yr)	q (au)	Q (au)	n	arc (d)	H (mag)	D_{SH}	D_{LS}	D_{D}	D_{R}	PHA
2011 EO ₄₀	1.6541021	0.54021638	3.36308	50.30833	17.06892	2.13	0.76	2.55	20	34	21.50	0.1198	0.0136	0.0396	0.0073	Yes
2011 GP ₂₈	1.5913963	0.51988326	4.04802	16.39708	252.18927	2.01	0.76	2.42	14	1	29.40	1.0474	0.0125	0.4904	0.0096	No
2002 AC ₉	1.7037203	0.56057681	2.28439	2.59440	28.42421	2.22	0.75	2.66	51	3132	21.00	0.4231	0.0429	0.1407	0.0225	Yes
2012 QZ ₁₆	1.5380029	0.50339326	6.12109	151.62989	258.93207	1.91	0.76	2.31	23	2	25.50	0.2902	0.0471	0.1007	0.0237	No
2012 VA ₂₀	1.6839686	0.55558020	4.39572	62.72875	240.13973	2.19	0.75	2.62	16	10	22.80	1.0052	0.0277	0.4055	0.0260	No
2013 BR ₁₅	1.5543524	0.52032940	1.95427	102.89583	284.89541	1.94	0.75	2.36	10	2	25.00	0.4426	0.0400	0.1464	0.0261	No
2009 SD	1.7327530	0.56634130	3.04578	344.32656	287.05641	2.28	0.75	2.71	24	3	25.40	1.0894	0.0392	0.5038	0.0261	No
2008 UM ₁	1.7553337	0.56564555	4.66126	208.94985	110.66782	2.33	0.76	2.75	8	1	32.10	0.9422	0.0359	0.3575	0.0278	No
1996 VB ₃	1.6269482	0.54485464	2.79698	180.59557	132.69687	2.08	0.74	2.51	21	9	22.40	0.9524	0.0316	0.3689	0.0294	No
2014 AF ₅	1.5675221	0.51935896	6.41544	100.66155	288.73603	1.96	0.75	2.38	24	1	28.80	0.4511	0.0450	0.1496	0.0301	No
2010 DU ₁	1.6865098	0.53929611	3.70444	147.83186	74.25038	2.19	0.78	2.60	22	4	26.50	1.0330	0.0186	0.4340	0.0336	No
2013 UX	1.6994450	0.56015033	5.45431	259.60985	51.62281	2.21	0.75	2.65	53	42	22.00	0.9725	0.0405	0.3800	0.0336	No
2004 RN ₂₅₁	1.6554455	0.52788736	4.39167	179.61123	245.93586	2.13	0.78	2.53	27	2	26.10	0.1716	0.0225	0.0608	0.0356	No
2008 EF ₃₂	1.6264297	0.52172394	1.73277	349.17117	112.28006	2.07	0.78	2.47	8	1	29.40	0.2353	0.0439	0.0768	0.0379	No
2007 BD ₇	1.5622989	0.49806111	4.84907	343.62635	219.85947	1.95	0.78	2.34	185	14	21.10	0.9241	0.0439	0.3660	0.0383	Yes
2011 CZ ₃	1.5962287	0.51076590	2.11312	326.23527	241.70608	2.02	0.78	2.41	30	4	26.30	0.9527	0.0437	0.3825	0.0426	No
2008 UT ₉₅	1.8148434	0.57460717	3.81217	220.05056	247.41560	2.44	0.77	2.86	32	2	27.40	0.3219	0.0443	0.1115	0.0447	No
2008 FH	1.5821116	0.50363499	3.45434	5.20697	264.09093	1.99	0.79	2.38	25	12	24.30	1.0304	0.0386	0.4814	0.0460	No
1996 AW ₁	1.5277410	0.51711311	4.73110	117.91581	228.70205	1.89	0.74	2.32	13	13	19.40	0.7543	0.0303	0.2670	0.0487	Yes

Table B3. All the meteorites in this table have recommended classification LL5 and their falls were observed. Source: Meteoritical Bulletin Database unless otherwise indicated (<http://www.lpi.usra.edu/meteor/metbull.php>). ¹ Gismelseed A. M., Bashir S., Worthing M. A., Yousif A. A., Elzain M. E., Al Rawas A. S., Widadallah H. M., 2005, *Meteoritics & Planetary Science*, 20, 255. ² Reed S. J. B., Chinner G. A., 1995, *Meteoritics*, 30, 468. ³ Wagner C., Arnold G., Wasch R., 1988, *Meteoritics*, 23, 93. ⁴ Al-Bassam K. S., 1978, *Meteoritics*, 13, 257. ⁵ Graham A. L., Michel-Levy M. C., Danon J., Easton A. J., 1988, *Meteoritics*, 23, 321. ⁶ Levi-Donati G. R., Sighinolfi G. P., 1974, *Meteoritics*, 9, 1. ⁷ Mason B., Wiik H. B., 1964, *Geochimica et Cosmochimica Acta*, 28, 533. ⁸ Muñoz-Espadas M. J., 2003, PhD thesis, Universidad Complutense de Madrid, Madrid, Spain. ⁹ Meszaros M., Ditrói-Puskás Z., Vácz T., Kereszturi Á., 2013, 44th Lunar and Planetary Science Conference, p. 1477. ¹⁰ Popova et al. (2013).

Name	Date fell	Fayalite (mol per cent)	Ferrosilite (mol per cent)	Wollastonite (mol per cent)	$\epsilon^{53}\text{Cr}$ ¹⁰
Chelyabinsk	2013 February 15	27.9±0.4/29.2±0.3 ¹⁰	22.8±0.8	1.3±0.3	0.23±0.03
Al Zarnkh ¹	2001 February 8	28	23		
Bawku ²	1989 December 29	26.8	22.6		
Salzwedel ³	1985 November 14	26.8	23.9		
Alta'ameem ⁴	1977 August 20	27	24.5		
Tuxtuac ⁵	1975 October 16	30	24.5	2	
Parambu ⁶	1967 July 24	28	22.5		
Guidder	1949 January 7				
Khanpur	1932 July 8				
Konovo	1931 May 26				
Paragould	1930 February 17				
Olivenza ^{7,8}	1924 June 19	29.1	25		0.23±0.06
Nyírábrány ⁹	1914 July 17	26.7	20.5		